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(19)

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(54) ELECTRO-OPTICAL APPARATUS FOR ROTATING THE PLANE OF POLARISATION OF A PLANE POLARISED LIGHT WAVE

(71) We, BBC BROWN BOVERI & CO. LTD., formerly Brown, Boveri and Company Limited, a corporation organised under the laws of the confederation of Switzerland, of Baden, Switzerland, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

The invention relates to an electro-optical unit for rotating the plane of polarisation of plane polarised light, and to the use of such a unit as a compensating element for a Faraday cell for measuring the current in a high-voltage conductor.

It is known to transform plane-polarised light into circularly polarised light by means of a quarter-wave plate in a diagonal position. It is further known to vary the polarisation of a light-wave by means of electro-optical elements, for example Pockels cells or Kerr cells, controlled by an electrical voltage (see for example, Scientific American, June 1968, page 17 *et seq.*).

Finally, it is known to rotate the plane of polarisation of a plane-polarised light-wave by means of a Faraday cell subjected to a magnetic field, and to use this effect to measure the current in high-voltage conductors in an electrically isolated manner (see for example French patent specification 1439260). In order to evaluate the signals obtained by means of this known arrangement, a method of compensation wherein the first Faraday cell is followed by a second one which cancels the rotation carried out in the first cell has proved to be satisfactory.

However, it is often not desired to use a second Faraday cell, for example on account of the magnetic field required.

The invention is therefore concerned with the problem of providing an optical unit with which the plane of polarisation of a plane-polarised light-wave can be rotated by the application of an electrical voltage. Such an electro-optical unit can be used with advantage not only in the arrangement mentioned for measuring currents in high-voltage conductors, but quite generally wherever it is desired to rotate the plane of polarisation by means of an electrical voltage.

The electro-optical element may be a Pockels cell or a Kerr cell. The principal axes of birefringence of the quarter-wave plates are advantageously parallel to one another and inclined at $\pi/4$ with respect to the principal axes of the electro-optical element.

According to the present invention there is provided electro-optical apparatus for producing an electrical signal representative of the varying orientation of the plane of polarisation of an incident light wave, comprising an optical unit arranged to rotate the plane of polarisation of said incident light wave and including two quarter-wave plates and an interposed electro-optical element of which the birefringence alters in accordance with an applied control voltage, together with means responsive to the orientation of the plane of polarisation of the light wave emerging from said optical unit by developing a control voltage which is applied to said electro-optical element so as substantially to nullify the rotation of the plane of polarisation of said incident light wave from a predetermined orientation, whereby said control voltage varies in accordance with the orientation of the plane of polarisation of the incident light wave.

Further details of embodiments of the invention will be apparent from the example

of embodiment described hereinafter with reference to the accompanying drawing, in which:

Figure 1 shows the construction and manner of action of the electro-optical unit forming a part of the invention; and

Figure 2 shows an arrangement for measuring a current in a high-voltage conductor by means of electro-optical zero-equalization of the Faraday cell.

In Figure 1, a plane-polarised light wave propagated in the direction indicated by arrow 18, for example from a laser or from a light-source followed by a polariser, impinges on a quarter-wave plate 1. Let the plane of oscillation of the incident light be inclined at an angle α to the plane of the drawing, as indicated in the circle 12. The main axes 4, 5 of the quarter-wave plate 1 are each inclined at $\pi/4$ to the plane of the drawing, so that they are symmetrical to that plane.

If the plane-polarised wave incident upon the quarter-wave plate 1 is described as being made up of two oppositely circularly polarised waves with a phase-shift of θ, the wave emerging from the quarter-wave plate 1 may now be considered as being made up of two plane-polarised waves inclined at $\pi/2$ with respect to one another and being themselves inclined at $\pi/4$ to the principal axes 4, 5 of the quarter-wave plate 1 and exhibiting a phase-difference of $\theta+\pi/2$.

The wave then passes through a Pockels cell 2, whereof one main axis 8 is parallel to the plane of the drawing. An electrical voltage V is then applied to this Pockels cell, and produces a phase-shift between the components of the transmitted wave in the direction of the main axes 8, 9. Suitable choice of the voltage V can thus compensate for the phase-difference θ, so that at the exit of the Pockels cell the light wave can be described as consisting of two light waves with a phase-difference of $\pi/2$ and plane-polarised in the directions of the main axes 8, 9.

The quarter-wave plate 3 which now follows again has its principal axes 6, 7 inclined at $\pi/4$ to the main axes 8, 9 of the Pockels cell 2, and thus inclined to the two plane-polarised waves. The wave oscillating in the direction of the axis 8 is therefore converted into a circularly polarised wave with one direction of rotation, and the wave oscillating in the axis 9 into a circularly polarised wave with the opposite direction of rotation, but these two circularly polarised waves now no longer exhibit any phase-difference, i.e. $\theta=0$. As may be seen, the two circularly polarised waves then reconstitute a plane-polarised wave having an inclination of $\alpha=0$ with respect to the plane of the drawing.

The arrangement described naturally not only enables an initially finite angle α to be compensated to zero, but quite generally enables a plane-polarised wave inclined at an angle α to be transformed into a linearly polarised wave having an inclination of $\alpha+k.V$, as is indicated in the circle 13 in Figure 1. In this connection, k is an apparatus constant determined by the Pockels cell.

If a Kerr cell is used instead of the Pockels cell, the angle of rotation is proportional to the square of the applied voltage V, that is so say the angle of inclination of the emergent linearly polarised wave is equal to $\alpha+k'V^2$, k' again being an apparatus constant.

In Figure 2, a plane-polarised light wave proceeds in the direction of line 18 from a laser 17 to a Faraday cell 14 which has a high-voltage conductor 15 wound round it, and the current which it is required to measure flowing in said conductor sets up a magnetic field in the Paraday cell 14. The Faraday cell is made of heavy flint glass or an yttrium-iron garnet, and rotates the plane of polarisation of the light wave through the angle α in proportion to the magnetic field produced by the current in the conductor.

The light wave inclined at the angle α now enters the electro-optical unit K, which is at earth potential as opposed to the Faraday cell 14, and which is built up from a quarter-wave plate 1, a Pockets cell 2 and a quarter-wave plate 3, as illustrated in Figure 1.

The Pockels cell is controlled by a voltage V produced by a means responsive to rotation of the plane of polarisation of the emergent light in such a manner that compensation is provided for the angle of inclination α of the incident light wave. For this purpose, there is conveniently provided a regulator arrangement comprising a polarising filter 16 following the electro-optical unit K and serving as an analyser, a photodetector 20 which measures the light-radiation passing through the filter 16, a phase-detector 21, an amplifier 22 and a differential amplifier 23. The differential amplifier 23 is fed on the one hand with the amplified output signal of the phase-detector 21, and on the other hand with a low-amplitude alternating voltage AC.

In the case of complete zero-equalization, only the second harmonic of the voltage AC appears at the photodetector 20, the frequency of the fundamental wave disappearing. On the contrary, if there is a finite equalisation error, there is a resultant current consisting of a d.c. component and the fundamental frequency of the signal AC, the phase of this current being opposite for positive and negative equalisation errors. The phase detector 21, which is preferably tuned to the frequency of the signal AC, is thus capable of delivering a signal which is unambiguously proportional to any equalisation error. This signal is, if necessary, amplified in the amplifier 22, and supplies the component of the control voltage V for equalising the angle of inclination α.

Since the signal is proportional to the angle of inclination α, and the latter is proportional to the current to be measured in the high-voltage conductor, the value of the current in the conductor can be measured from the reading of the measuring instrument 24.

The amplification of the regulator circuit may be so great that substantially ideal zero-equalisation takes place at the photodetector 20.

WHAT WE CLAIM IS:—

1. Electro-optical apparatus for producing an electrical signal representative of the varying orientation of the plane of polarisation of an incident light wave, comprising an optical unit arranged to rotate the plane of polarisation of said incident light wave and including two quarter-wave plates and an interposed electro-optical element of which the birefringence alters in accordance with an applied control voltage, together with means responsive to the orientation of the plane of polarisation of the light wave emerging from said optical unit by developing a control voltage which is applied to said electro-optical element so as substantially to nullify the rotation of the plane of polarisation of said incident light wave from a predetermined orientation, whereby said control voltage varies in accordance with the orientation of the plane of polarisation of the incident light wave.

2. Apparatus in accordance with claim 1 wherein the electro-optical element is a Pockels cell.

3. Apparatus in accordance with claim 2 wherein the electro-optical element is a Kerr cell.

4. Apparatus in accordance with any one of the preceding claims wherein the principal axes of birefringence of the quarter-wave plates are inclined at $\pi/4$ with respect to the principal axes of the electro-optical element.

5. Apparatus in accordance with any one of the preceding claims wherein said control voltage is derived from a differential amplifier of which one input is arranged to be fed with a fixed-frequency alternating voltage and the other input is fed with the output signal of a phase detector controlled by said alternating voltage and of which the input is connected to a photodetector receiving light which has passed through said electro-optical unit and through a subsequent analyser.

6. Apparatus in accordance with any one of the preceding claims when used to respond to the orientation of the plane of polarisation of light passed through a Faraday cell controlled by the current in a high-voltage electrical conductor.

7. Electro-optical apparatus for measuring the current in a high-voltage electrical conductor substantially as described with reference to Figure 2 of the accompanying drawing.

8. Electro-optical apparatus for producing an electrical signal representative of the varying orientation of the plane of polarisation of an incident light wave substantially as described with reference to Figures 1 and 2 of the accompanying drawings.

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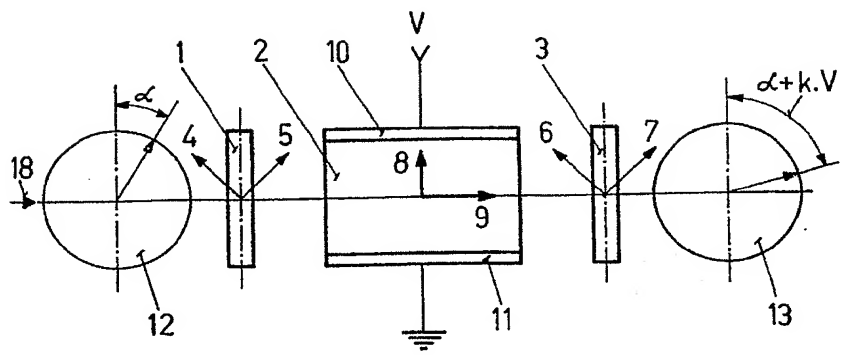
V
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12
11
13

Fig.1

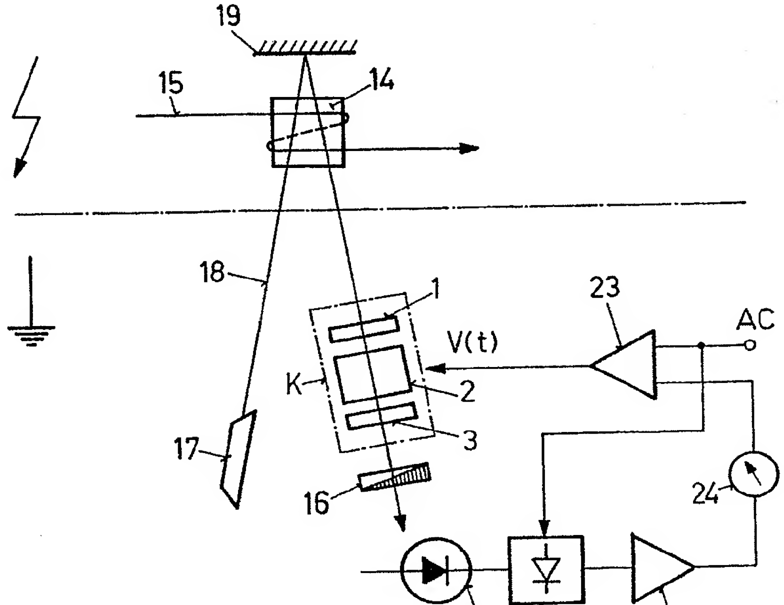
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Fig.2